Dangerous FEP Events: Real-Time Data of Ground and Satellite CR Measurements Using for Monitoring of Beginning and Forecasting of Expected Particle Fluxes in Atmosphere and in Space

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Abstract

We describe the underlying principles of an algorithm to provide an early warning on a dangerously high flux of solar flare energetic particle (FEP) in near-earth orbits. The algorithm is based on real-time one-minute neutron monitor (NM) data that include different multiplicities. A large increase in the NM counts in all channels indicates the possible initiation of a large FEP event. The next one-minute data are used for checking whether the observed increase indeed corresponds to the beginning of real large FEP event. If this is the case, determination of the energy spectrum of the approaching solar particles is attempted. We show that the time of ejection, diffusion coefficient in the interplanetary space and the energy spectrum in source can also be estimated from the NM and satellite on-line data. The algorithm is applied to the NM measurements on Mt. Gran-Sasso during the large FEP event of September 1989. The predicted particle fluxes are compared with the fluxes measured by GOES. This comparison indicates that the spectrum determined from the data collected within 10–12 minutes after the detection of the FEP event provides a stable forecast of the peak fluxes. This research is partly supported by the INTAS grant 0810.

1. Introduction

Sudden increase of energetic particle fluxes due to a large solar Flare Energetic Particle (FEP) event presents a significant hazard to satellites in near-Earth orbits. This hazard is serious especially for geo-stationary and polar orbits. The enhanced flux lead to considerable ionizing dose deposition in electronic components, as well as to a high rate of single event effects, such as bit-flips (SEU),

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latch-up (SEL) and burn-out (SEB). The destructive effects of such events can be mitigated, if the components are turned off before the event starts. This is possible only if a reliable forecast of FEP event is provided. Current forecasts of radiation storms have high false-alarm rates, since most events are not Earth-directed. We propose a novel forecast method that utilizes Earth-based observations, which is inherently immune to false alarms.

2. Main Idea

The most dangerous part of the FEP spectrum for the satellite electronics is the low-energy ($\sim$ 30–300 MeV) particles, due to their high flux and efficient energy deposition. They reach near-Earth orbits several hours after the event occurs in the Sun. The high energy ($>$ 10 GeV) particles of the FEP event reach the Earth with velocity near that of light. Their flux is very low, but they can be detected by ground-based neutron monitors (NM). Early detection of an Earth-directed FEP event by NM and calculation of its intensity will provide an alert, with very low false-alarm probability [1]. We apply the coupling function method [2] using 1-minute counts for different multiplicities from a single observatory to predict the spectrum of the approaching particles [3]. Alternatively, total counts from several stations can be used [4].

3. Forecast Steps

1. Search for a significant increase (larger than 2.5σ) in the total counts of the last 1, 2, or 5 one-minute data. If found, go to state Alert-1. If not, continue search.
2. While in state Alert-1: Estimate the rigidity spectrum of the FEP event above the atmosphere: $\Delta D(R)/D_o(R) = bR^{-\gamma}$ where $D_o(R)$ is the background galactic CR spectrum. Calculate best fits for b and γ using data for at least 2 different multiplicities. Coupling function methods are used at this step.
3. Evaluate the energy-dependent diffusion constant in the interplanetary space using the rigidity spectra calculated from three previous one-minute data. This allows determination of the energy spectrum at the source, by solving for the inverse problem.
4. Using the source spectrum and the diffusion constants, predict the near Earth spectrum for a time window of $\sim$ 1 hour. Compare on-line GOES measurements of the last several minutes (if available) to previous predictions, in order to refine the next predictions.
5. If the predicted flux at 100 MeV exceeds pre-determined threshold, issue Alert-2
6. Repeat steps 2–5, until total count returns to background level (below 2.5 σ).

4. Equations

Coupling functions W: $W_{om}(R) = a_m k_m R^{-(k_m+1)} \exp(-a_m R^{-k_m})$
m = multiplicity, R = rigidity; a_m and k_m are determined from latitude surveys
Determination of exponent γ from equation:

$$F_m(R_c,\gamma)/F_n(R_c,\gamma) = [\Delta I_m(R_c)/I_{mo}(R_c)]/[\Delta I_n(R_c)/I_{no}(R_c)]$$

m, n = multiplicities, R_c = rigidity cut-off at station, I is the measured CR intensity
Factor b determined from: $\Delta I_m(R_c)/I_{mo}(R_c) = bF_m(R_c,\gamma)$
Diffusion coefficient in interplanetary space:

$$K(R) = \left(-\frac{r^2}{4}\left(\frac{1}{t_1}-\frac{1}{t_2}\right)\right)\left(\ln\left(\frac{b(t_1)}{b(t_1)}\left(\frac{t_1}{t_2}\right)^{3/2} R^{-(\gamma(t_1)-\gamma(t_2))}\right)\right)^{-1}$$

Estimation of spectrum in source:

$$N_o(R) = 2\pi^{1/2} b(t_1) R^{-\gamma(t_1)} D_o(T)(K(R)t_1)^{3/2} \exp(r^2(4K(R)t_1))$$

Forecasting to time t at r = 1 A.U.:

$$N(R,r,t) = N_o(R)[2\pi^{1/2}(K(R)t)^{3/2}]^{-1} \times \exp\left(-\frac{r^2}{4K(R)t}\right)$$

5. September 1989 Event as a Test Case

We used one-minute NM data for total neutron intensity and different multiplicities data (from 1 to 8) on Mt. Grand Sasso as well as GOES-7 data. In Fig. 1–3 is shown the evolution of the forecasted fluxes with time and comparison with the observed GOES fluxes. In these figures by full lines are shown fluxes forecasted by using CR data up to time t, for E > 100 MeV, 1 GeV and 3 GeV; by circles are shown the observed on GOES fluxes for E > 100 MeV.

From Fig. 1–3 can be seen that the using CR data for the first 5 min of increase gave very rough forecast, for 10 min data — little better, but for 40 min data the forecast up to 2500 min is practically coincide with observations on GOES satellite.

6. Conclusions

1. It is possible to forecast the intensity of an upcoming radiation storm using 1-minute counts of cosmic ray intensities for different multiplicities.

2. The algorithm is demonstrated for a historical event.

3. Additional verification for other historical events is underway.

4. An operational alert system based on this algorithm will be developed, and operated using CR data from Emilio Segré Observatory (Israel) on Mt. Hermon.

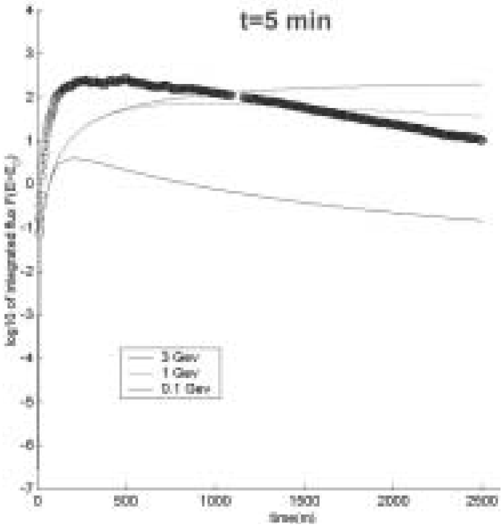

Fig. 1. For t = 5 min

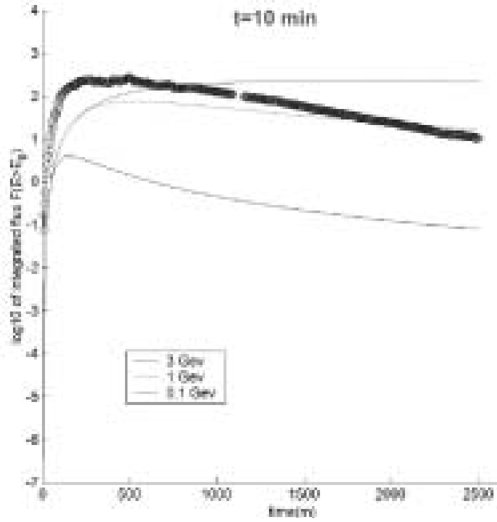

Fig. 2. For t = 10 min

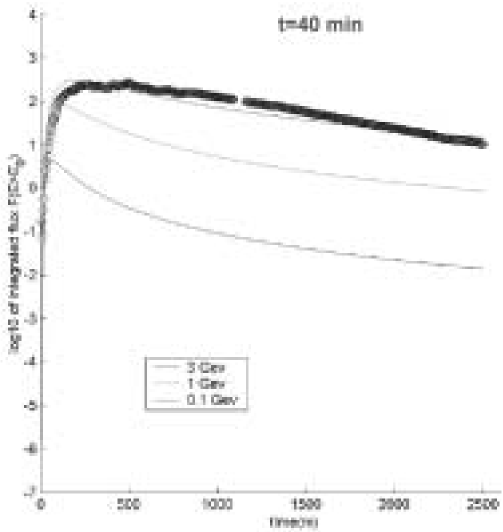

Fig. 3. For t = 40 min

7. References

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